

Nucleon structure in the search for new physics

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Abstract. We report on recent results on nucleon structure that are helping guide the search for new physics at the precision frontier. Results discussed include the electroweak elastic form factors, charge symmetry breaking in parton distributions and the strangeness content of the nucleon.

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INTRODUCTION

The Standard Model has been enormously successful at describing experiments in nuclear and particle physics. The search for new physical phenomena beyond the Standard Model is primarily driven by two complementary experimental strategies. The first is to build high-energy colliders, such as the Large Hadron Collider (LHC) at CERN, which aim to excite a new form of matter from the vacuum. The second, more subtle approach is to perform precision measurements at moderate energies, where an observed discrepancy can signify the existence such new forms of matter.

The significance of measurements at the precision frontier depends on careful experimental techniques, in conjunction with robust theoretical predictions of contributing Standard Model phenomena. Here we report on some recent progress in nucleon structure that is contributing to the low-energy search for new physics. In particular, the nucleon electroweak elastic form factors and charge symmetry breaking in parton distributions both play a significant roles in precision tests of the weak interaction. In the context of ongoing dark matter searches, improved knowledge of the strangeness scalar content of the nucleon is leading to better constrained predicted cross sections.

QUARK WEAK CHARGES

At low energies, the weak interaction is manifest in the effective current–current correlators

$$\mathcal{L}_{PV} = -\frac{G_F}{\sqrt{2}} \sum_q [C_{1q} \bar{e} \gamma^\mu \gamma_5 e \bar{q} \gamma_\mu q + C_{2q} \bar{e} \gamma^\mu e \bar{q} \gamma_\mu \gamma_5 q] \quad (1)$$

where G_F is the weak coupling constant, and the C_{iq} denotes flavour-dependence of the effective neutral current interaction — at tree level they are simply $C_{1(2)q} \sim g_e^{A(V)} g_q^{V(A)}$. The full couplings are determined within the Standard Model by combining precision Z-pole measurements [1] with the scale evolution to the low-energy domain [2, 3].

Experimental constraints on the weak neutral current at low energies have been rather limited. One celebrated result is the precision measurement of atomic cesium's $6s \rightarrow 7s$ transition polarizability, and the resulting extraction of the weak nuclear charge of cesium [4]. The weak charge extraction depends crucially on the precision calculation of the atomic wave functions, where the latest theoretical update gives $Q_w^{Cs} \equiv -376C_{1u} - 422C_{1d} = -73.16(29)_{\text{exp}}(20)_{\text{th}}$ [5] — in complete agreement with the Standard Model value $-73.15(2)$ [6]. This agreement with the Standard Model is depicted by the narrow, almost horizontal (orange) band in Figure 1.

The cesium measurement places very restrictive bounds on the form of parity-violation interactions within new physics scenarios. In terms of a generic contact interaction describing new physics [3]

$$\mathcal{L}_{PV}^{\text{new}} = -\frac{g^2}{4\Lambda^2} \bar{e} \gamma^\mu \gamma_5 e \sum_q h_V^q \bar{q} \gamma_\mu q, \quad (2)$$

the cesium measurement, at 1-sigma, restricts the magnitude of any new physics contribution to be less than

$$\frac{g^2}{\Lambda^2} (0.67h_V^u + 0.75h_V^d) \sim [7\text{TeV}]^{-2}. \quad (3)$$

The atomic measurements are mostly insensitive to hadronic or nuclear structure because of the small energy transfers involved¹. In electron scattering, the neutral current can be probed by measuring parity-violating asymmetries. Given the typical energy scales involved, the extraction of the weak interaction parameters also requires knowledge of nucleon structure. Measurements of this sort date back to the pioneering work of Prescott *et al.* [8] at SLAC, where a parity-violating asymmetry in deep inelastic scattering was measured (see the almost vertical band in Figure 1).

More recently, measurements of the parity-violating *elastic* scattering asymmetries have now been carried out by a number of experiments, including: SAMPLE at MIT-Bates [10]; PVA4 at Mainz [11, 12, 13]; and G0 [14] and HAPPEX [15, 16, 17] at Jefferson Lab. The principal focus of these programs was the study of the electroweak form factors of the nucleon, and particularly, the determination of the strange quark component of these form factors.

In addition to the study of the electroweak structure, the kinematic coverage of these measurements, together with the standard electromagnetic form factors, provides a reliable extrapolation to the $Q^2 \rightarrow 0$ limit, and thereby an extraction of the proton's weak charge [9]. Figure 2 displays this extrapolation, where the observed scattering asymmetries (projected onto the forward limit) are shown. The displayed asymmetry has been normalised to give the weak charge of the proton at $Q^2 = 0$. The slope of the line describes the knowledge of the neutral current form factors.

The extraction of the proton's weak charge from this modern data improves on the earlier results by about a factor of 5 — see the ellipse in Figure 1. Following the generic

¹ Though such effects will become increasingly more significant as higher-precision measurements are performed, see Ref. [7], for instance

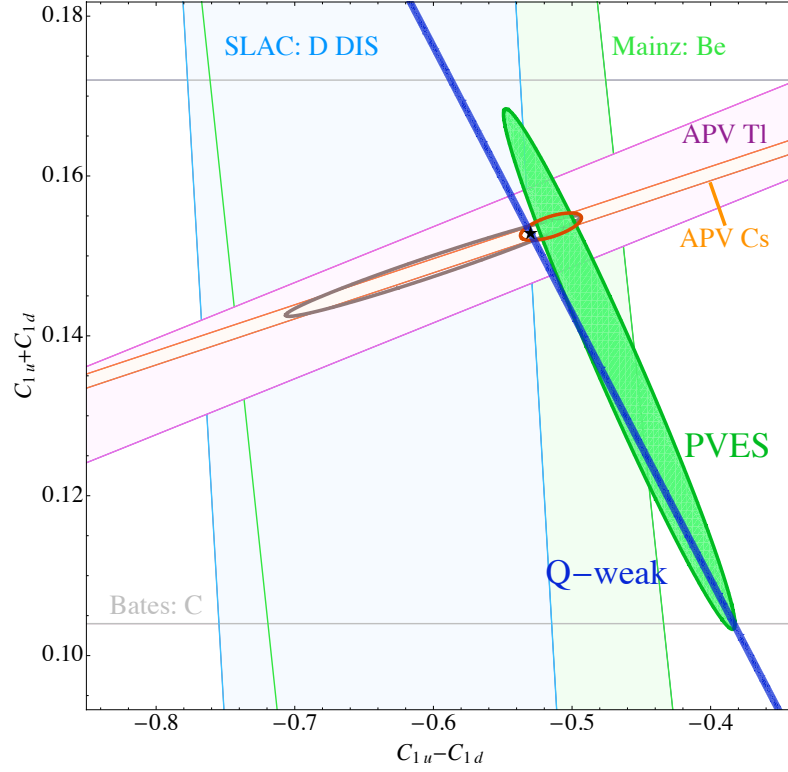


FIGURE 1. Summary of experimental determination of the weak charges of quarks [9]. The Q-weak band indicates the anticipated precision of the experiment currently in progress, drawn arbitrarily in agreement with the Standard Model.

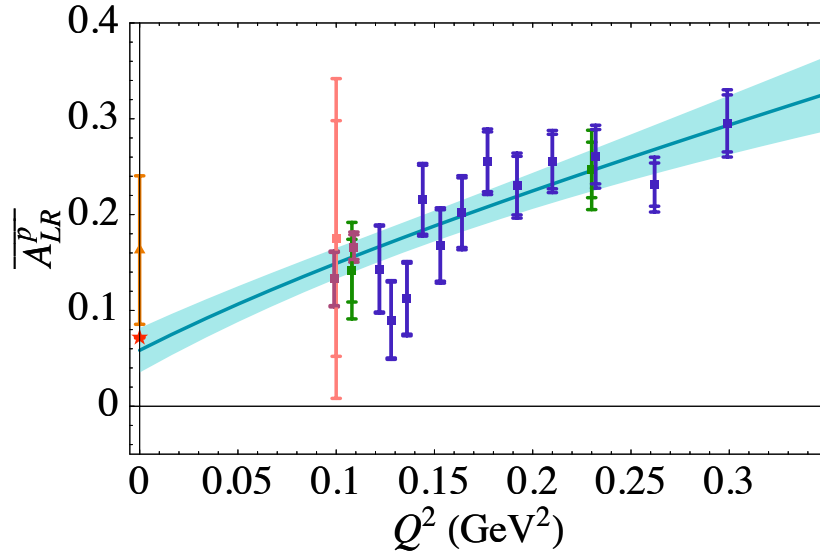


FIGURE 2. Scaled parity-violating asymmetries measured on a proton target, projected onto the forward-angle limit. The normalisation is selected such that the $Q^2 \rightarrow 0$ limit describes the weak charge of the proton, $Q_w^p = -2(2C_{1u} + C_{1d})$.

contact interaction described above, the observed agreement with the Standard Model sets the characteristic mass scale to above $\sim 2\text{ TeV}$ (at 1-sigma).

CHARGE SYMMETRY BREAKING IN PARTON DISTRIBUTIONS

With the improved technology and expertise gained in performing the precision measurements of the electroweak elastic form factors, there are now plans to revisit parity-violation in DIS [18]. This program is proposing to improve the precision of the early SLAC measurements of Prescott et al. by roughly an order of magnitude.

The new Jefferson Lab program is aiming at a sub-1% measurement of the PVDIS asymmetry from deuterium. With possible contributions from supersymmetry, for example, estimated to be as large as $\sim 1\%$ [19], this program is just at the threshold of a Standard Model test² — provided Standard Model corrections are well understood.

One of the potentially largest hadronic corrections to the physics asymmetry is that arising from charge symmetry violation (CSV). Based on the phenomenological extraction by Martin et al. [20], the 90% confidence level bounds on CSV lead to $\sim 1.5\text{--}2\%$ variations in the PVDIS asymmetry [21]. At typical kinematics of the JLab program, such fluctuations appear to be more significant than other possible corrections, such as higher twist [21, 22] or target-mass corrections [23].

With CSV (potentially) at the scale of $\pm 1.5\text{--}2\%$ of the PVDIS asymmetry, a precision measurement could provide the best direct measurement of charge symmetry violation in parton distributions. While such a measurement would be of great interest for hadronic physics [24, 25], it will disguise any signature of new physics. Fortunately lattice QCD offers the opportunity to constrain this hadronic physics independently. In a recent study, lattice calculations of the hyperon quark momentum fractions have been used to extract charge symmetry breaking in nucleon parton distributions [26]. These results suggest CSV in the quark momentum fractions of $\sim 0.20 \pm 0.06\%$, corresponding to a $\sim 0.4\text{--}0.6\%$ correction to the PVDIS asymmetry. Importantly, the statistical precision represents an order of magnitude improvement on the bounds reported in Ref. [20].

With future work to constrain the systematics of the lattice calculation of CSV and continued theoretical development in higher-twist and target mass corrections, mentioned above, there is a strong case that the PVDIS program at JLab will be able to provide an important new low-energy test of the Standard Model.

We also note that the lattice result of [26] also makes an important contribution to the famous NuTeV anomaly [27]. Whereas the original report of a 3-sigma discrepancy with the Standard Model assumed CSV to be negligible, the value extracted from the lattice acts to reduce this discrepancy by 1-sigma. The remaining 2-sigma also appear to be naturally described within the Standard Model as a nuclear medium modification effect [28, 29].

² Of course, in conjunction with other low-energy measurements, correlations can enhance the significance of possible new physics limits.

STRANGENESS SCALAR CONTENT

The strange quark condensate in the nucleon is of particular significance in the current search for dark matter. The relatively large coupling of strange quarks to candidate dark matter, combined with a typically large uncertainty in the strangeness sigma term, have led to considerable variation in the predicted cross sections for direct detection measurements [30, 31].

The traditional method for extracting the strangeness sigma term in the nucleon, σ_s , uses the observed hyperon spectrum in conjunction with the pion-nucleon sigma term [32, 33]. Even with a perfect extraction of the light-quark sigma term and best-estimates of higher-order corrections [34], this method is limited to an uncertainty in σ_s of $\sim 90\text{MeV}$ [35].

Advances in lattice QCD calculations now provide significantly better constraint on the strangeness sigma term [35]. There is general consensus that the strangeness sigma term is on the small side of early estimates [36, 37, 38, 39, 40, 41] — with a couple recent hints that it may not be quite so small [42, 43].

A small strange quark sigma term leads to a dramatic reduction in the uncertainties of dark matter cross sections [44]. For a range of candidate supersymmetric models of dark matter, the predicted cross sections are found to be substantially smaller than previously suggested.

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REFERENCES

1. S. Schael, et al., *Phys.Rept.* **427**, 257–454 (2006), hep-ex/0509008.
2. W. Marciano, and A. Sirlin, *Phys.Rev.* **D29**, 75 (1984).
3. J. Erler, A. Kurylov, and M. J. Ramsey-Musolf, *Phys.Rev.* **D68**, 016006 (2003), hep-ph/0302149.
4. S. Bennett, and C. E. Wieman, *Phys.Rev.Lett.* **82**, 2484–2487 (1999), hep-ex/9903022.
5. S. Porsev, K. Beloy, and A. Derevianko, *Phys.Rev.Lett.* **102**, 181601 (2009), 0902.0335.
6. K. Nakamura, et al., *J.Phys.G* **G37**, 075021 (2010).
7. B. Brown, A. Derevianko, and V. Flambaum, *Phys.Rev.* **C79**, 035501 (2009), 0804.4315.
8. C. Prescott, W. Atwood, R. Cottrell, H. DeStaebler, E. L. Garwin, et al., *Phys.Lett.* **B84**, 524 (1979).
9. R. D. Young, R. D. Carlini, A. W. Thomas, and J. Roche, *Phys.Rev.Lett.* **99**, 122003 (2007), 0704.2618.
10. D. Spayde, et al., *Phys.Lett.* **B583**, 79–86 (2004), nucl-ex/0312016.
11. F. Maas, et al., *Phys.Rev.Lett.* **93**, 022002 (2004), nucl-ex/0401019.
12. F. Maas, K. Aulenbacher, S. Baunack, L. Capozza, J. Diefenbach, et al., *Phys.Rev.Lett.* **94**, 152001 (2005), nucl-ex/0412030.
13. S. Baunack, K. Aulenbacher, D. Balaguer Rios, L. Capozza, J. Diefenbach, et al., *Phys.Rev.Lett.* **102**, 151803 (2009), 0903.2733.
14. D. Armstrong, et al., *Phys.Rev.Lett.* **95**, 092001 (2005), nucl-ex/0506021.
15. K. Aniol, et al., *Phys.Rev.* **C69**, 065501 (2004), nucl-ex/0402004.
16. K. Aniol, et al., *Phys.Lett.* **B635**, 275–279 (2006), nucl-ex/0506011.
17. A. Acha, et al., *Phys.Rev.Lett.* **98**, 032301 (2007), nucl-ex/0609002.
18. P. Reimer, K. Paschke, X. Zheng, et al., Jefferson Lab Experiment E1207102.

19. A. Kurylov, M. Ramsey-Musolf, and S. Su, *Phys.Lett.* **B582**, 222–228 (2004), hep-ph/0307270.
20. A. D. Martin, R. G. Roberts, W. J. Stirling, and R. S. Thorne, *Eur. Phys. J.* **C35**, 325–348 (2004), hep-ph/0308087.
21. T. Hobbs, and W. Melnitchouk, *Phys.Rev.* **D77**, 114023 (2008), 0801.4791.
22. S. Mantry, M. J. Ramsey-Musolf, and G. F. Sacco, *Phys.Rev.* **C82**, 065205 (2010), 1004.3307.
23. T. Hobbs (2011), 1102.1106.
24. J. Londergan, D. Murdock, and A. W. Thomas, *Phys.Rev.* **D73**, 076004 (2006), hep-ph/0603208.
25. J. T. Londergan, J. C. Peng, and A. W. Thomas, *Rev. Mod. Phys.* **82**, 2009–2052 (2010), 0907.2352.
26. R. Horsley, Y. Nakamura, D. Pleiter, P. Rakow, G. Schierholz, et al. (2010), 1012.0215.
27. G. P. Zeller, et al., *Phys. Rev. Lett.* **88**, 091802 (2002), hep-ex/0110059.
28. I. Cloet, W. Bentz, and A. Thomas, *Phys.Rev.Lett.* **102**, 252301 (2009), 0901.3559.
29. W. Bentz, I. C. Cloet, J. T. Londergan, and A. W. Thomas, *Phys. Lett.* **B693**, 462–466 (2010), 0908.3198.
30. A. Bottino, F. Donato, N. Fornengo, and S. Scopel, *Astropart.Phys.* **13**, 215–225 (2000), hep-ph/9909228.
31. J. R. Ellis, K. A. Olive, and C. Savage, *Phys.Rev.* **D77**, 065026 (2008), 0801.3656.
32. J. Gasser, *Annals Phys.* **136**, 62 (1981).
33. A. E. Nelson, and D. B. Kaplan, *Phys.Lett.* **B192**, 193 (1987).
34. B. Borasoy, and U.-G. Meissner, *Annals Phys.* **254**, 192–232 (1997), hep-ph/9607432.
35. R. D. Young, and A. W. Thomas, *Nucl.Phys.* **A844**, 266C–271C (2010), 0911.1757.
36. H. Ohki, H. Fukaya, S. Hashimoto, T. Kaneko, H. Matsufuru, et al., *Phys.Rev.* **D78**, 054502 (2008), 0806.4744.
37. R. Young, and A. Thomas, *Phys.Rev.* **D81**, 014503 (2010), 0901.3310.
38. D. Toussaint, and W. Freeman, *Phys.Rev.Lett.* **103**, 122002 (2009), 0905.2432.
39. H. Ohki, S. Aoki, H. Fukaya, S. Hashimoto, T. Kaneko, et al., *PoS LAT2009*, 124 (2009), 0910.3271.
40. J. Martin Camalich, L. Geng, and M. Vicente Vacas, *Phys.Rev.* **D82**, 074504 (2010), 1003.1929.
41. K. Takeda, et al. (2010), 1011.1964.
42. S. Collins, G. Bali, A. Nobile, A. Schafer, Y. Nakamura, and J. M. Zanotti, *PoS LATTICE2010*, 134 (2010), 1011.2194.
43. R. Babich, R. C. Brower, M. A. Clark, G. T. Fleming, J. C. Osborn, et al. (2010), 1012.0562.
44. J. Giedt, A. W. Thomas, and R. D. Young, *Phys.Rev.Lett.* **103**, 201802 (2009), 0907.4177.